The important role of diagnostics for the structural recovery of historic buildings

The Important Role of Diagnostics for the Structural Recovery of Historic Buildings

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Abstract: Diagnostic tests represent a fundamental phase of knowledge for historical masonry buildings. The correct design of structural recovery and seismic improvement work must be based on the results of the preliminary tests, for a better knowledge of the vulnerabilities and the mechanical characteristics of ancient masonry structures. The Italian technical codes have given great importance to the level of knowledge reached on the existing buildings, promoting the investment of diagnostics as a fundamental phase of the design work. Two case studies of multidisciplinary diagnostic tests, carried out on monumental buildings, are described for the preliminary evaluation of the quantitative and qualitative characteristics of the masonry structures. In both cases the tests allowed to better understand the vulnerabilities of the masonry section and to design the most appropriate strengthening work. The interpretation of the results coming from tests of different typologies allowed to investigate in depth the hidden peculiarities of the historical masonry structures.

Keywords: Diagnostic tests, Historic masonry buildings, Strengthening work, Non-destructive tests, Knowledge level.

1. INTRODUCTION

The need to secure the existing architectural heritage requires the complete knowledge of the mechanical characteristics of the masonry structures. Often structural vulnerabilities and material degradation are hidden inside the structure and not visible. Therefore non-invasive or semi-invasive technologies are needed to investigate the historical building. Structural diagnostics is a very important field of engineering in both civil and monumental buildings. The current Italian technical codes [1-3] have focused attention on the need to reach an adequate level of knowledge of the masonry structures to allow a correct design of strengthening work. In particular the Circolare 21/01/2019 [2] introduces the confidence factor whose value is a function of three progressive levels of knowledge achieved by means of diagnostic tests on the masonry structures. The confidence factor appears in the denominator of the equation (1) that determines the design value of the masonry strength:

$$f_d = \frac{f_m}{FC \cdot \gamma_m} \tag{1}$$

where f_d is the design compressive strength; f_m is the medium value of compressive strength (obtained from a table of the Circolare21/01/2019); FC is the confidence factor relating to the level of knowledge achieved (Table **1**); γ_m is the material coefficient in accordance with the semi-probabilistic method used by Italian technical codes and by the Eurocode.

The maximum investment in the diagnostic phase allows to know in greater detail the mechanical characteristics of the masonry, and therefore to decrease the factor FC. A lower value of the FC corresponds to having a higher value of the design strength. Therefore, the greater the investments in the diagnostics, the lower the intervention costs will be, as the designer will have more certainties on the mechanical strength of the materials and on the quality of the masonry texture (Figure **1**). Often structural recovery work proved to be incorrect in the choice of materials and techniques as the historical building had not been analyzed in depth [4, 5].

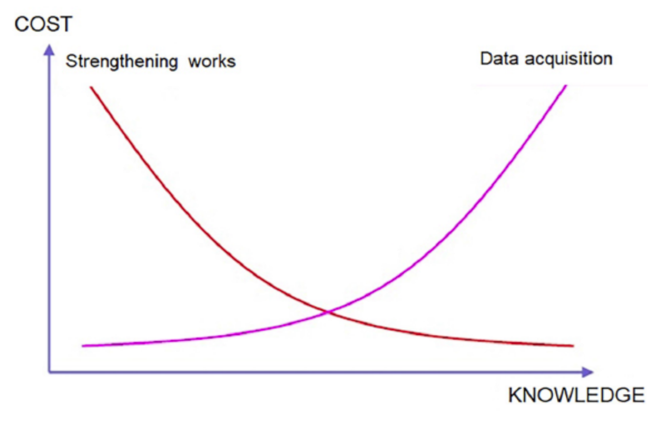

Figure 1: Diagram cost – knowledge.

In particular, historic buildings need non-invasive investigative techniques, especially when frescoed

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Table 1: Confidence Factor for Levels of Knowledge

Level of knowledge	Survey and Tests	FC
LC1 (limited knowledge)	Geometric survey. In situ limited checks of construction details. In situ limited tests for the properties of materials.	1,35
LC2 (adequate knowledge)	Geometric survey. In situ extensive and exhaustive checks of construction details. In situ extensive tests for the properties of materials.	1,20
LC3 (accurate knowledge)	Geometric survey. In situ extensive and exhaustive checks of construction details. In situ exhaustive tests for the properties of materials.	1,00

walls are to be investigated. Therefore, diagnostic techniques based on the passage of sonic [6] and thermographic [7] signals, or tests carried out on samples prepared directly in the laboratory without demolishing in situ structures should be encouraged.

Figure 2: The Royal Palace of Venaria.

Figure 3: The Sanctuary of Santa Maria delle Grazie at Varoni, near Amatrice.

Two case studies of multidisciplinary application of different diagnostic techniques are described for two monumental buildings: the Royal Palace of Venaria and the Sanctuary of Santa Maria delle Grazie in Varoni (Amatrice). The Royal Palace of Venaria, Unesco site near Turin (Italy), is one of the Savoy Residences belonging to the large Circuit of Royal Residences that characterizes the Baroque architecture (17^{th} century) around Turin (Figure **2**). It was the largest restoration site in Europe, completed in 2007 and currently one of the most visited museums in Italy [8]. The Sanctuary of Santa Maria delle Grazie is a church of the 15^{th} century that was damaged by the Central Italy earthquake in 2016 (Figure **3**). In both cases the different diagnostic tests, carried out both in situ and in the laboratory, allowed to investigate with greater precision the mechanical characteristics of the masonry structures and to correctly design the subsequent strengthening work.

2. TESTS METHODS AND RESULTS

2.1. The Royal Palace of Venaria

The restoration and refurbishment of the Royal Palace of Venaria provided for the reconstruction of the entire mezzanine floor with a new functional archives destination for museum.The ancient mezzanine floors were made of wood and had been completely destroyed. The area of the mezzanine floor between the first and second floors was about 1000 square meters. The Government Department responsible for monuments decided to rebuild this mezzanine floor made by steel beams and corrugated sheets, counter-ceilings on the intrados. However, the masonry needed a more in-depth analysis of their mechanical strength to verify if they would have resisted the increase in exercice loads due to the insertion of the new floors and the new use of archives.

Figure 4: Flat jacks test carried out at the Royal Palace of Venaria.

For this reason, flat jacks tests were carriedout (Figure **4**). This partially destructive technique provided for the execution of a horizontal cut in the wall (through the mortar joints of the brick or stone walls) inside which is inserted a flat jack. The relaxation that occurs along the direction perpendicular to the cutting plane determines the approach between the two edges of the crack; the pressure necessary to recover the original distance of the parts, re-established by the oil sent under pressure inside the jack, corresponds to the strain acting at the measuring point before cutting (test with single jacks). A second cut was made, about 50 cm above or below the first one, and it was possible to perform a monoaxial compression test (test with double jacks) from which the tension-deformation diagram of the masonry and the mechanical strength were obtained [9].

The compressive strength values obtained from the 6 flat jacks tests were lower than needed to bear, with the safety coefficients, to the exercice loads related to the new construction of the mezzanines (Table **2**). The values were also very variable depending on the points of execution.

Table 2: Results of the Flat Jacks Tests Carried out at the Royal Palace of Venaria

Flat Jacks Tests	Operating Compressive Strain (MPa)	Compressive Strength (MPa)
FJ1	0,52	1,97
FJ2	0,33	1,58
FJ3	0,52	1,38
FJ4	0,79	2,82
FJ5	0,58	1,75
FJ6	0,93	1,98

Sonic tests were also performed (Figure **5**). Sonic measurements are the non–destructive technique most frequently used. The test technique consists in generating a series of sound impulses (impacts) and in the consequent recording of the moments of arrival of the signal on the other surface of the masonry wall. The excitation and reception points are distinct and separated by a known distance and are chosen according to the areas of the artefact to be investigated. The data processing consists in measuring the time that the pulse takes to cross the section of material placed between generator and receiver and in the analysis of the wave signal. The aim of the sonic test is to evaluate the homogeneity of the masonry structure. The speed of propagation of the waves is directly related to the mechanical and physical characteristics of the material investigated, in the case in which it is homogeneous and isotropic. The sonic test can evaluate the homogeneity of the masonry texture by highlighting the presence of voids, defects or cracks.

A masonry wall with a compact texture will have a high sonic speed (>2000 m/s) because the signal will not encounter obstacles due to voids, cracks or heterogeneous material. A masonry with sonic speed between 1000 and 2000 m/s will have a discrete quality. Finally, below a sonic speed of 1000 m/s a poor quality of the wall texture corresponde, in which the waves take more time to cross the thickness due to the presence of voids and heterogeneity of the material that can refract the waves [10]. The results of the 14 survey points performed on the walls of the Royal Palace highlighted low average values, compatible with a poor quality masonry due to the presence of very heterogeneous material.

Figure 5: Sonic tests carried out at the Royal Palace of Venaria.

Table 3: Results of Sonic Tests of the Royal Palace of Venaria

Sonic test	Average Speed (m/s)	Compressive Strength from Flat Jacks (MPa)
S1	546	
S2	894	
S3	779	
S4	1218	
S5	798	
S6	1291	1,98
S7	1480	
S8	779	1,75
S9	1881	
S10	1175	
S11	686	
S12	543	
S13	872	
S14	439	

Therefore the masonry needed to be consolidated in order to bear the future exercice loads of the mezzanines floors. It was also necessary to evaluate a solution to support the steel beams of the new floor to the walls without making too many breaks inside the structural section of the masonry, assessed the low quality of themasonry texture.The masonry walls could be consolidated with the technique of lime mortar injections or with the jacketing walls technique. The choice had to be tested to evaluate its preventive correctness in relation to the mechanical and qualitative characteristics of the historical masonry [4].

The injection technique consisted by making the binding mixture penetrate, by pouring under pressure into the voids present through the nozzles, so as to restore and improve the mechanical characteristics of the masonry wall for the most effective distribution of the forces acting, caused by the elimination of the voids.

The reinforced plaster was a technique for improving the characteristics of the masonry that is widely used for renovating existing masonry buildings. In practice it consisted in applying on the two sides of the wall of metal meshes or FRP (Fiber Reinforced Polymer) connected to each other. In this way the jacketing wall technique allowed to reach the following objectives: improvement of the characteristics of the masonry due to the plating and confinement of the material; introduction of tensile-resistant structural elements, such as metal meshes and GFRP (Glass Fiber Reinforced Polymer) meshes, while ordinary masonry is not considered tensile-resistant; increase of the structural thickness of the masonry.

The technology offers a wide range of materials for this operation and each of these has individual characteristics that must be taken into account in the design phase. Fundamental and essential characteristics are the anti-shrinkage (or better, compensated shrinkage) and guarantee a chemical-physical-mechanical compatibility with the mortar and aggregates that must be consolidated. For both strengthening techniques it was preferable to use lime-based mortars, since this materials are more compatible with the mechanical characteristics of the historic masonry compared to cement [4, 5].

To achieve an effective evaluation, 6 specimens (800x800x400mm) were prepared on site using bricks and stones to create a masonry texture similar to the existing one. Two of them were tested as original historic masonry, so they did not receive any strengthening work. Two other specimens have been strengthened by means of the lime mortar injections technique. Finally, the last two samples were strengthened using jacketing technique reinforced by iron mesh (Figure **6**). The specimens have been tested at the Laboratory of the Politecnico di Torino by compression test (Figure **7**). Before reaching the cracking load, the elastic modulus of the specimen was evaluated. By evaluating the slope of the elastic stretch of the load-displacement curves, it was also possible to derive the stiffness of the masonry specimen The aim was to evaluate the structural response, in terms of

Figure 6: (**a**) Original masonry specimens; (**b**) masonry specimens strengthened by injection technique; (**c**) masonry specimens strengthened by jacketing wall technique.

Figure 7: Compression test of: (**a**) original masonry specimens (MU); (**b**) masonry specimens strengthened by injection technique (MUI); (**c**) masonry specimens strengthened by jacketing wall technique (RMA).

Table 4: Results of Compression Test

Specimen	Typology	P_{max} (KN)	$P_{average}$ (KN)	E (N/mm^2)	$E_{average}$ (N/mm^2)	K (N/mm)	$K_{average}$ (N/mm)
MU 01	Historical masonry	600.69	**532.37**	7062	**7147**	1126705	**1117404**
MU 02	Historical masonry	464.04		7231		1108102	
MUI 01	Injected masonry	515.95	**514.05**	4913	**4435**	1287808	**1283092**
MUI 02	Injected masonry	512.14	***-3.44%***	3956	***-37.95%***	1278376	***+14.83%***
RMA 01	jacketing walls	769.75	**869.04**	5931	**6940**	1099971	**1306238**
RMA 02	jacketing walls	968.33	***+63.24%***	7948	***-2.90%***	1512505	***+16.90%***

improvement of strength and the elastic properties, that the techniques could offer for that type of historical masonry.

The values shown in the Table **4** show how the strengthening technique made by injections is even worse for this type of historical masonry, as it would result in an almost zero increase in strength and a decay of the elastic modulus with respect to the original situation of original masonry. This would even lead to a slight stiffening of the masonry wall. On the contrary, the application of the reinforced plaster offers a good increase in compressive strength, which is not too excessive, and at the same time does not alter the value of the original elastic modulus of the historical masonry. In the field of structural reinforcement it is very important not to alter the original properties of the historical masonry structure [4, 5].

The results of further experimentation in the laboratory have therefore validated the choice of jacketing wall technique for the reinforcement of the historical masonry structures of an area of the Royal Palace to allow the construction of the new mezzanine floors (Figure **8**). The choice of the reinforced plaster was also well combined with the technical solution adopted for the insertion of the steel beams of the floors, where was preferred to use the steel anchors for hanging the support plates rather than to break the wall perimeter (Figure **9**). The jacketing wall technique made it possible to reinforce these anchorage points as well.

Figure 8: Jacketing wall technique made in the Royal palace of Venaria.

The choice of anchor length and diameter was also performed by evaluating the important results of the preliminary pull-out test carried out on the original masonry walls (Figure **9a**).

2.2. The Sanctuary of Santa Maria delle Grazie at Varoni

Structural diagnostics acquires particular importance in the evaluation of damage to historic buildings in seismic area. The design of the seismic improvement of the building must take into account all the vulnerabilities and the damages, even hidden, that can influence the structural safety [11]. The Central Italy earthquake damaged many churches, as buildings that are structurally more vulnerable to dynamic actions. Many cracks and out of plane collapses shown during the last earthquake were due to classical seismic damage mechanisms of the churches [3, 12].

The Sanctuary of Santa Maria delle Grazie at Varoni is one of these churches that during the different phases of the earthquake swarm has suffered some damage mainly due to the vulnerability of the masonry texture and the connections between the walls. After the first major seismic shock of 24th August 2016, some cracks had opened on the walls of the church and in correspondence with the arch of the apse. But above all, the façade had given signs of out-of plane

Figure 9: (**a**) Pull-out test; (**b**) stell anchor for the hang of the beams support; (**c**) support steel plates anchored; (**d**) construction of the new mezzanines floors.

Figure 10: (**a**) Signs of the execution of reinforcement injections on the walls of the church; (**b**) second iron tie carried out in pairs with the one existing at the triumphal arch.

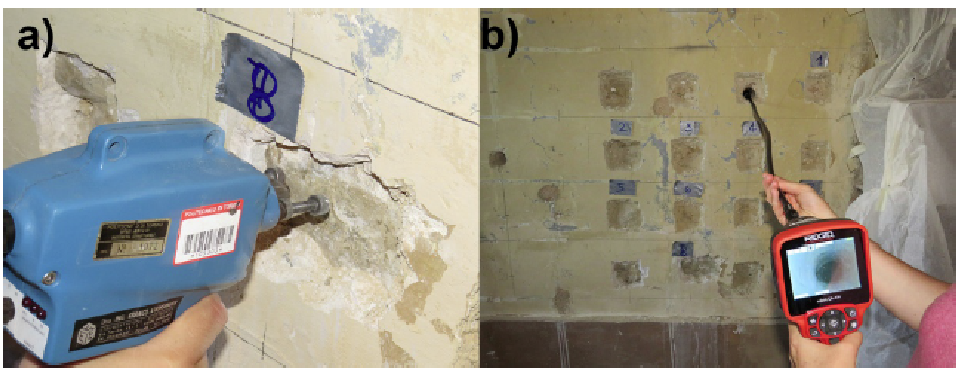

Figure 11: (**a**) Sonic test; (**b**) endoscopy in the same area of the sonic test.

mechanism. Following the detection of these damage, the façade had propped by means of large metal profiles. As there was still doubt, not yet verified, of a wall texture with two large unlinked layers, the Government Department responsible for monuments tried to improve the mechanical performance of the damaged walls with lime mortar injections technique that had not been extended to the full depth of the masonry texture, but only superficially because of the fear that they would not be lost in the eventual emptiness between the two masonry layers (Figure **10**). The temporary safety works also consisted of the insertion of an additional iron tie along the damaged masonry arch of the apse.

Also in this case the Government Department responsible for monuments commissioned the execution of a series of diagnostic tests to learn more about the characteristics of the masonry structures. The evaluation of the compressive strength and of the elastic modulus of the masonry structures was performed by flat jacks technique. The low values found (Table **5**) showed that, despite the high resistance of the individual stones, the strong degradation of the mortar greatly influences the mechanical performance of these stone wall structures typical of the historical construction of Amatrice.

Table 5: Results of the Flat Jacks Tests

Operating Compressive Strain (MPa)	Elastic Modulus (MPa)	Compressive Strength (MPa)
0,3	1220	1,0

However, the only values obtained from the flat jacks tests were not sufficient to confirm if the masonry wall was multilayer and how much the reinforcement injections had improved the quality of the masonry texture. Non-invasive diagnostic tests came in support to deepen the knowledge of the masonry quality. On a portion of the masonry surface, the sonic test was performed to evaluate both the presence of any voids within the masonry stratigraphy and to validate the intervention of reinforcement injections. In fact, if the injections of mortar have effectively filled the voids inside the masonry, the sonic velocities increase due to the better masonry quality. Therefore, often sonic tests are performed after a similar reinforcement technique to validate its effectiveness [10].

A portion of the wall surface was divided into several equidistant points, in correspondence of which the sonic test was performed with an impact hammer (Figure **11a**). Endoscopy was also performed in the same test area (Figure **11b**).

Table 6: Results of Sonic Tests

Test Point	Average Speed (m/s)
P 2.5	419
P 2.6	368
P 3.3	1044
P 3.4	837
P 3.5	531
P 3.6	409
P 4.3	761
P 4.4	663
P 4.5	549
P 4.6	618
P 5.4	1125

The values taken from the sonic test are on average low and related to a low quality masonry texture. Together with the images taken from endoscopy (Figure **12**), sonic tests also confirm the presence of two large wall layers combined and the presence of some intermediate voids. Therefore the low speed values confirm that the injections did not fill all the voids and did not improve the wall quality.

The technicians of the Government Department responsible for monuments took into account the results that emerged to evaluate the most appropriate seismic improvement techniques to be implemented for the church.

3. DISCUSSION

Both case studies highlighted the considerable importance of diagnostic tests for a better knowledge of historical buildings. The in-depth analysis of the masonry quality was fundamental both to have a correct vulnerability assessment and to choose the most suitable strengthening technique for improving the mechanical strength of the masonry structures [11, 12]. Both in the restoration site of the Royal Palace of Venaria and in that of the Sanctuary of Santa Maria delle Grazie at Varoni, the surveys pair of sonic-flat jacks tests was very useful for mutually validating the experimental results. The sonic test offers the advantage to extend in other areas of the building, by means of a non-destructive way, the confirmation of the experimental data obtained in a semi-destructive way by the double flat jack test, to be limited both for the high cost of execution and for the greater invasiveness. Both case studies have shown how is variable the quality of the masonry texture found in a historic building. Often the masonry qualities are different even within the same building, due to the different construction phases that have occurred in history. Structural vulnerabilities and masonry quality are often not directly visible. A good compromise between limited semi-destructive tests and extensive non-destructive tests can provide the necessary mechanical strength values (indispensable for carrying out the structural calculations) and a certain evaluation of the quality of the historic masonry texture.

The results of the diagnostic tests will also be useful for the choice of the most compatible strengthening

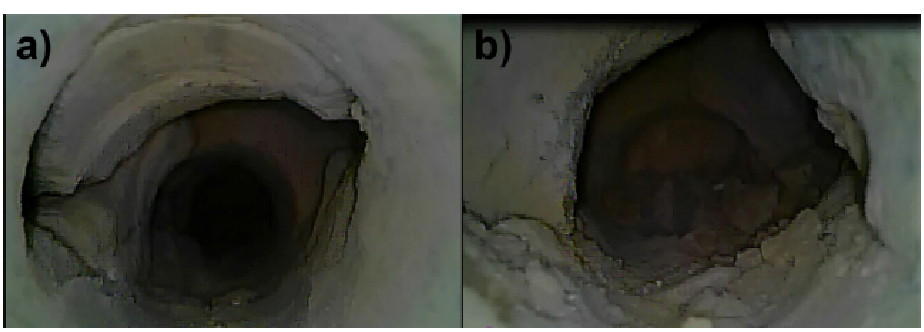

Figure 12: Images of the endoscopy: (**a**) first discontinuity; (**b**) second discontinuity at the boundary between the two wall layers.

material in comparison to the mechanical characteristics of the historical masonry. In particular, the experimental determination of the elastic modulus of the masonry is of fundamental importance, for example to choose a mortar for injection or for the reinforced plaster with the similar deformation characteristics in comparison to the historical masonry in which it will be applied [4, 5].

In both examples the diagnostic tests, performed in situ and also in the laboratory, made it possible not to make a mistake in the choice of the strengthening technique. The laboratory tests carried out for the Royal Palace of Venaria have shown how sensitive is the validity of the strengthening design hypothesis through the injections work. This technique can be very valid only if the masonry texture has certain requisites that can penetrate the mortar and fill in the voids. Otherwise, in the presence of a granulometric curve of the grout mortar that does not conform to the dimensions of the internal voids, or when there is a compact masonry texture, the injection technique is ineffective, although the table C.8.5.II in the Circolare 21/01/2019 [2] suggests considering a 20% increase in mechanical performance. Hence the importance of always performing tests on specific masonry texture. The same tests carried out confirmed the data in the table C.8.5II [2] of regarding an increase in mechanical strength by means of reinforced plaster around 50%.

In the case of the Sanctuary of Santa Maria delle Grazie at Varoni, the sonic tests were essential both to evaluate the effectiveness of the injections work, in this case performed at a reduced depth and therefore not effective, and to demonstrate the presence of a double wall layer. The subsequent seismic improvement work, as announced by the Government Department responsible for monuments, will mainly concern the insertion of tie rods to improve the building's box-like behavior.

4. CONCLUSIONS

Preliminary diagnostics must become a necessary step in the culture of the good designer who is preparing to evaluate the static and seismic safety of the historical building. Only the results of multidisciplinary diagnostics can guarantee a more correct design, aware of the real value of the mechanical characteristics of the structures and its vulnerabilities. The experience of many strengthening work has shown that the absence or lack of diagnostic results has often led the designer to make incorrect or unnecessary assessments regarding strengthening interventions.

The correlation of the results of different types of tests has allowed to know more in depth both the mechanical characteristics of the masonry and the quality of the masonry texture. In particular, the knowledge of hidden vulnerabilities, such as ineffective connections between walls and multilayer walls, is essential to counteract out of plane kinematic of the walls that are very dangerous under seismic action.

The paper illustrated some of the most used techniques in the field of structural diagnostics for historic buildings, applied to important restoration building sites, as the Royal palace of Venaria and the Sanctuary of Santa Maria delle Grazie at Varoni. Within these restoration sites, the considerable importance that the experimental results have had for the choice of the most appropriate strengthening technique for the historic building was demonstrated.

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